Real-Time Fractional Order PI for Embedded Control of a Synchronous Buck Converter

Maximiliano Bueno-Lopez, Eduardo Giraldo

***Abstract*—In the last years, control theory has applied fractional calculus, and the results are unquestionable. The classic PI controllers have been modified with fractional calculus creating the Fractional Order Proportional-Integral (FOPI). The FOPI controllers have performed better than conventional PI because they provide more flexibility in the controller design. The use of PI controllers remains of high impact on modern power systems, and for this reason, it is important to continue analyzing their implementation with some variants. One of the elements that continue to be most studied in modern power systems is the converter and, recently, the synchronous Buck converter that increases the efficiency reducing the conduction losses. In this work, a novel real-time fractional order control approach is applied over a Synchronous Buck converter. The results are validated in simulation and under a Real-Time simulator. In order to evaluate the performance of the proposed FOPI controller, two scenarios are considered: variable reference and variable load, where the proposed FOPI controller outperforms the classical PI controller.**

***Index Terms*—Embedded control, fractional-order PI, real-time.**

I. Introduction

THE Proportional-Integral-Differential (PID) controllers monopolize most of the process control applications [1]. Industry prefers PID controllers over other more advanced techniques because of the ease and good performance [2], [3]. A power converter is a device used in modern modern power systems and microgrids, and PI controllers are the most commonly used in this systems [4], the derivative action is normally not used in such systems [5], [6]. The classic PI control can be modified and combined with different methods, and one of these is the fractional calculus. It is important to mention that this strategy has been used mainly in chemistry and physics systems [2], [7]. Applications are usually focused on the industry but with the results presented in this article, it is possible to identify good performance also in microgrids and power systems.

Other contribution of fractional-order controller is presented in [8], where it is possible to see how the technique works in irrational transfer function models that appear in large-scale systems, such as networks of mechanical/electrical elements and distributed parameter systems.

Fractional order systems have also been combined with artificial intelligence, for example in [9] was proposed an optimal control approach based on fractional-order PI-Fuzzy-PI (FOPI-Fuzzy-FOPI) for reactive power in a wind farm system. In [10] a Fuzzy logic controller and then a fractional order proportional integral (PI) controller were using for the regulation and the stability of the DC voltage during transient states and under various operating conditions in the three-level neutral-point-clamped (NPC) inverter. One more application where a novel genetic optimize multi-control adaptive fractional order PID (AFOPID) for Photovoltaic (PV) and Wind connected grid system is presented in [11].

Recently, some applications of Fractional Order PI (FOPI) have been seen in power electronics and renewable energies [12], [11], [13], [14], [15], [16]. For example, in [17] was presented a traditional PI and enhanced FoPID (Fractional order PID) to scale down current harmonics, balance loads by MSALC (Modified Shunt Active Line Conditioner) using traditional PI and enhanced FoPID (Fractional order PID) control. Research into DC–DC converters involves plenty of techniques proposed to improve performance, efficiency and modeling, however, the study and application of PI controllers remains the biggest reference in these systems.

Taken into account the above, in this paper, an embedded Fractional Order Proportional-Integral (FOPI) controller is proposed, evaluated and validated in simulation and in real-time over a Synchronous Buck converter. A detailed comparison analysis is performed for two scenarios: reference tracking and variable load. The comparison is performed by considering the proposed approach and a classical PI controller, which is the most used controller for this type of application.

The main contributions of this paper are given as follows: (a) A reduction of the settling-time for a closed loop response in the Synchronous Buck converter, by improving the classical PI controller by a FOPI controller, (b) An implementation structure in real-time, based on a C2000 Delfino microcontroller, which allows embedded evaluation of the controller over a real Synchronous Buck converter. The paper is organized as follows: In section II, a detailed description of the FOPI controller is proposed, applied over a Synchronous Buck converter. In section III, the experimental setup and the evaluation of the proposed approach over a simulated and a real Synchronous Buck converter are presented. And finally, in section IV the conclusions and future works are presented.

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II. Material and Methods

A. Fractional Order PI Control

The classical PI control is the most used control strategy for Buck, Boost and Buck-Boost DC-DC converters. The transfer function of a PI controller can be defined as

$$C(s) = K_p + \frac{K_i}{s} \tag{1}$$

where the Laplace transform of the control signal $U(s)$ is computed as

$$U(s) = C(s)E(s) \tag{2}$$

being $E(s)$ the Laplace transform of the tracking error.

On the other hand, the transfer function of a PI$^\lambda$ can be expressed as:

$$C(s) = K_p + \frac{K_i}{s^\lambda} \tag{3}$$

with $U(s) = C(s)E(s)$ being $E(s)$ the Laplace transform of $e(t)$, with $e(t)$ the tracking error. In [18] a discrete fractional operator is defined as

$$s^\lambda = \left(\frac{1-z^{-1}}{T}\right)^\lambda \tag{4}$$

By applying a binomial expansion of (4), the discrete time fractional order operator can be obtained

$$I^\lambda = T^\lambda \sum_{j=0}^{\infty} c_j z^{-j} \tag{5}$$

being c_j defined as

$$c_j = \left(1 - \frac{1-\lambda}{j}\right) c_{j-1} \tag{6}$$

with $j = 1, 2, \ldots$ and $c_0 = 1$. The main advantage of the fractional control is the possibility of giving more degrees of freedom the order of the integral (λ) action [19]. The following fractional-order PI^λ is proposed:

$$u[k] = K_p e[k] + K_i T^\lambda \sum_{j=0}^{L} c_j e[k-j] \tag{7}$$

being L the number of samples of the window and being c_j defined as (6).

B. Synchronous Buck Converter

In [20], a dynamical model for a Buck converter is presented, where a classical PI control approach is successfully evaluated. On the other hand, in [21] is shown a comparison of the efficiency of the Buck converter against the Synchronous Buck converter. This effect is also considered by a modified control structure, as proposed in [22]. In this work, the PI or FOPI control strategies are applied over a Buck converter with a synchronous structure. In Fig. 1 is shown the simplified diagram of a Synchronous Buck converter with a fixed and switchable load.

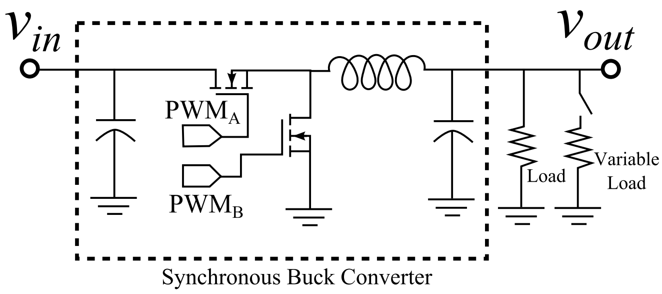

Fig. 1. Simplified diagram of the Synchronous Buck converter

It is worth noting that the simplified diagram of Fig. 15 is based on a CSD87588N NexFET Power Block by Texas Instruments, which is a Half-Bridge Power Block highly-optimized design for synchronous Buck with 90% System Efficiency at 20A applications, offering high current and high efficiency. From Fig. 1, it is worth mentioning that the load is designed by considering two parallel resistors: a fixed 7.5Ω resistor, and a switchable 2Ω resistor.

III. Results

In order to evaluate the proposed fractional order PI approach, a comparison analysis is performed with a classical PI controller. The system is evaluated by using detailed simulation considering the Simscape Matlab toolbox by including the PWM generation. In addition, an evaluation over a real system is performed by considering an embedded real-time controller over a Texas Instruments C2000 Delfino microcontroller. The analysis is performed under two scenarios: a variable desired reference for voltage mode control, and a constant desired reference under variable load.

In the first scenario, a variable reference is selected with values of 2V, 3V, and 2.5V, which are modified every 20 milliseconds. The parameters of the classical PI controller are selected as $K_p = 0.002$ and $K_i = 0.003$. The closed-loop simulation results for output voltage and reference are shown in Fig. 2.

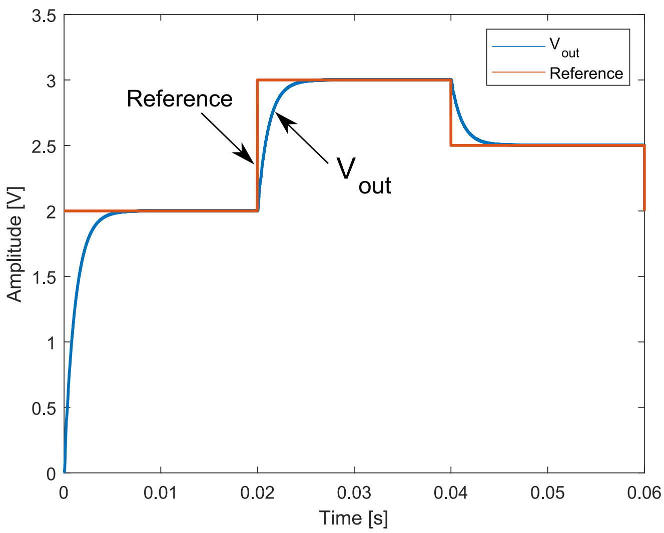

Fig. 2. Output voltage variable reference tracking results by using a detailed simulation

The closed-loop result for the inductor current, which are related to the voltage reference tracking of Fig. 2, is shown in Fig. 3.

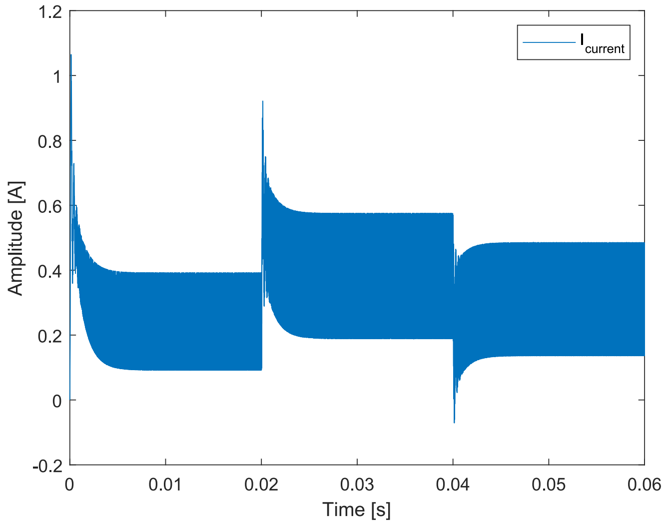

Fig. 3. Inductor Current under variable reference detailed simulation scenario

The duty cycle related to the control signal, for the voltage reference tracking of Fig. 2, is shown in Fig. 4.

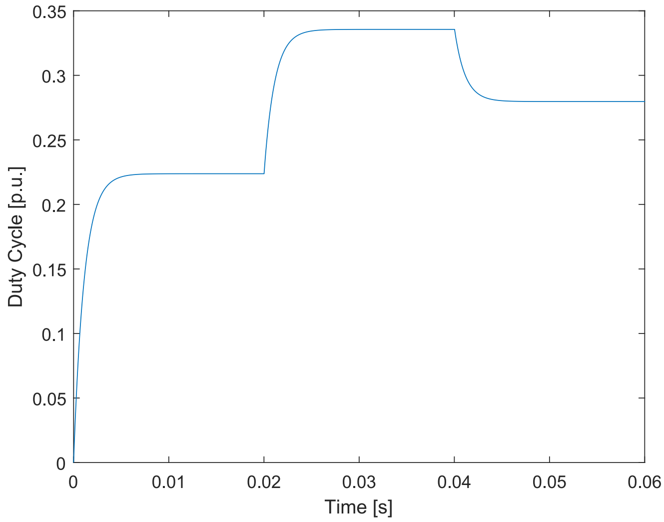

Fig. 4. Duty cycle under variable reference detailed simulation scenario

In the second scenario, a variable load is considered. To this end, the load is modified a $t = 30$ milliseconds, by switching on the additional resistor depicted in Fig. 15. In this case, the reference voltage is set constant to 2V, and the parameters of the classical PI controller are selected as $K_p = 0.002$ and $K_i = 0.003$. The resulting voltage tracking behavior is depicted in Fig. 5.

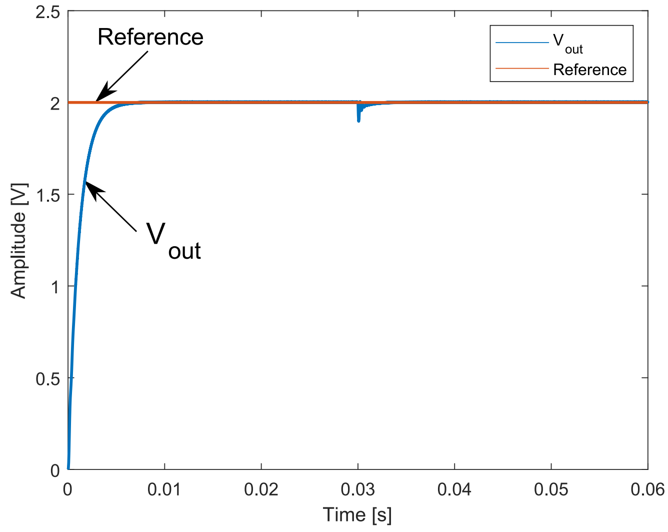

Fig. 5. Constant reference variable load scenario with Load change at $t = 30$ milliseconds

The closed-loop result for the inductor current, which are related to the voltage reference tracking of Fig. 5, is shown in Fig. 6.

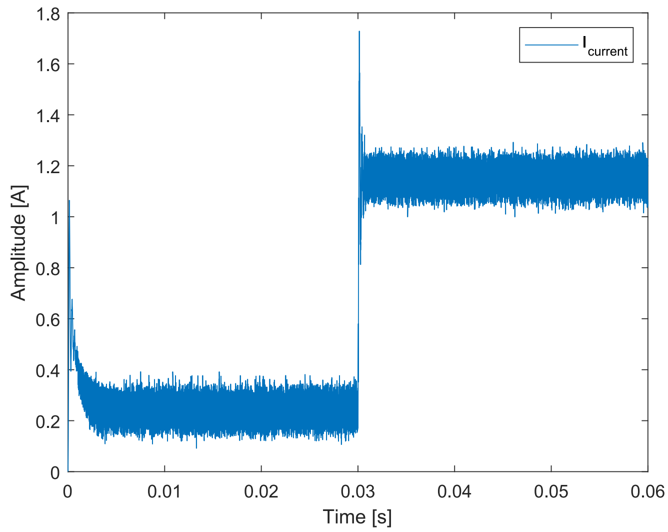

Fig. 6. Inductor Current under variable load scenario

The duty cycle related to the control signal, for the voltage reference tracking of Fig. 5, is shown in Fig. 7.

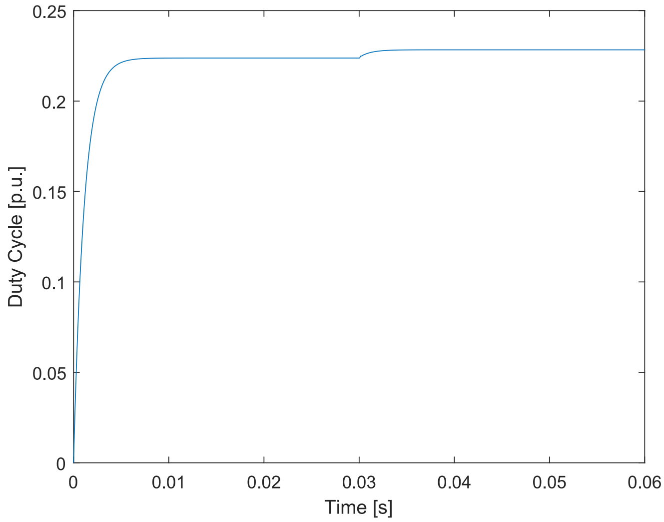

Fig. 7. Duty cycle of the variable load scenario

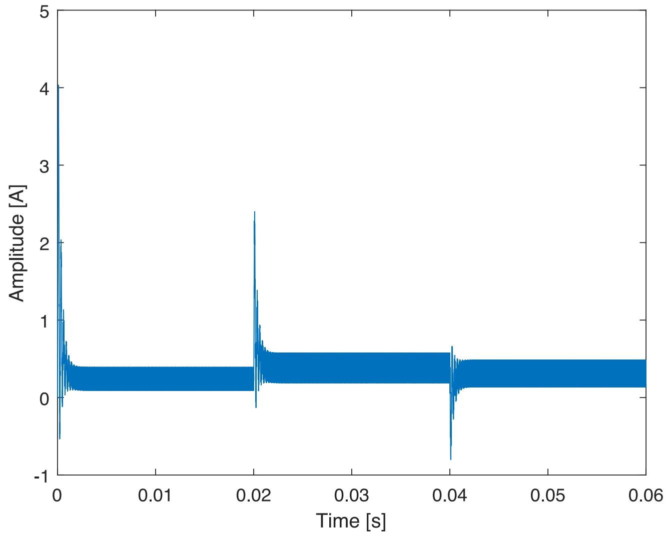

Fig. 9. Inductor Current under variable reference for fractional order PI detailed simulation scenario

The proposed Fractional Order PI controller is also evaluated under simulation, by considering the same controller parameters $K_p = 0.002$ and $K_i = 0.003$ with a $\lambda = 0.5$. For the first scenario, a variable reference is also selected with values of 2V, 3V, and 2.5V, which are modified every 20 milliseconds. The resulting reference tracking performance for the FOPI controller is presented in Fig. 8.

For the second scenario, a variable load is also considered a $t = 30$ milliseconds for the proposed FOPI controller. The reference voltage is also set constant a 2V. The obtained results are presented in Fig. 10.

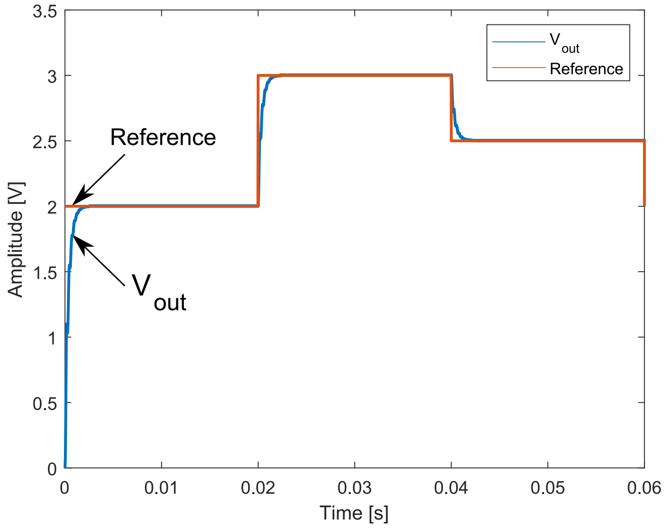

Fig. 8. Output voltage variable reference for fractional order PI detailed simulation

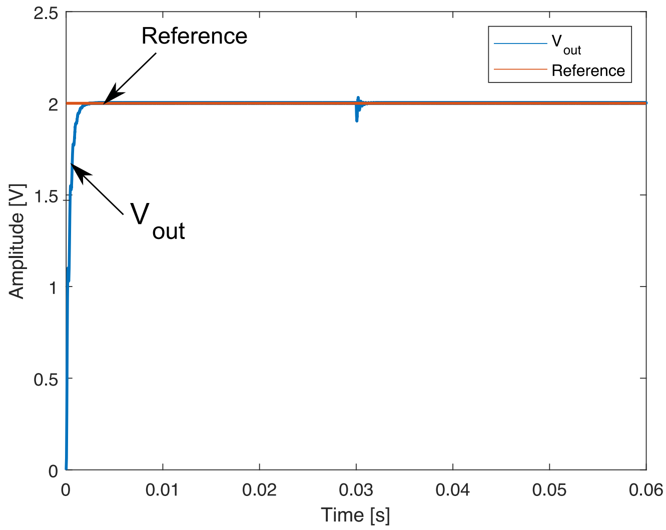

Fig. 10. Output voltage Variable load for fractional order PI detailed simulation

The closed-loop inductor current under the variable reference tracking of Fig. 8 is presented in Fig. 9.

The inductor current for the variable load scenario of Fig. 10 is presented in Fig. 11.

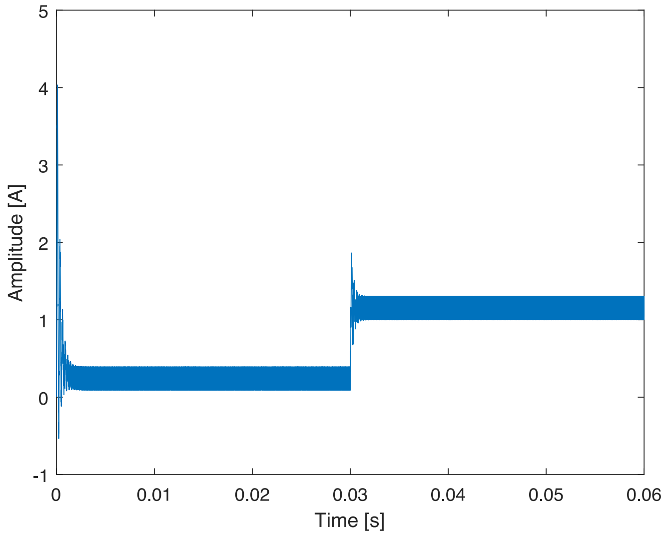

Fig. 11. Inductor Current under variable load for fractional order PI detailed simulation scenario

A comparison for reference tracking for voltage by considering the classical and fractional order PI is shown in Fig.12.

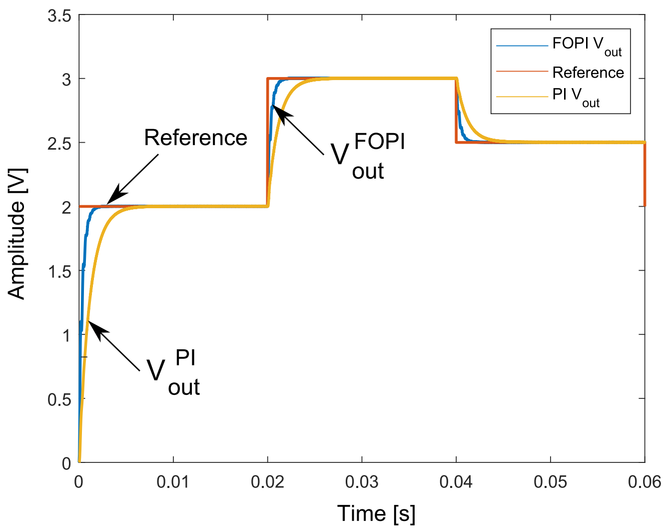

Fig. 12. Output voltage Variable reference for classical and fractional order PI detailed simulation

A comparison for reference tracking under variable load for voltage by considering the classical and fractional order PI is shown in Fig.13.

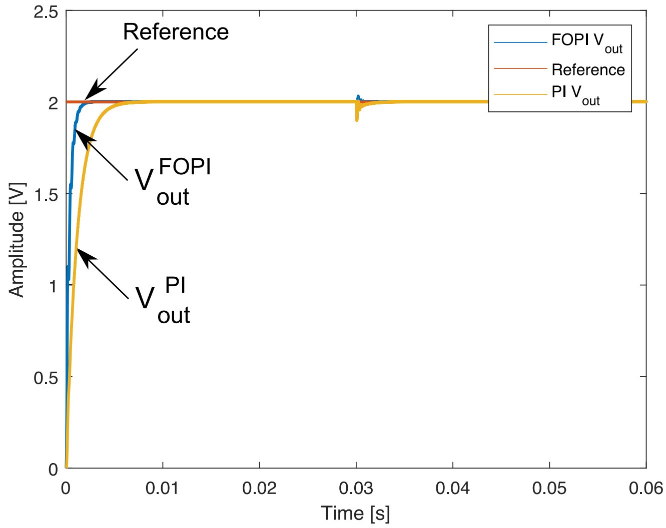

Fig. 13. Output voltage Variable load for classical and fractional order PI detailed simulation

A zoom around the load switch is shown in Fig. 14, where the closed loop system response can be observed more clearly.

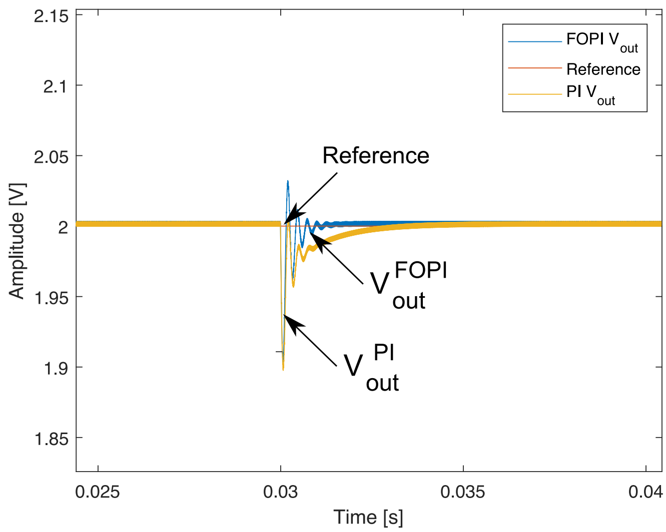

Fig. 14. Output voltage zoom under variable load for classical and fractional order PI detailed simulation

It is worth mentioning that form Fig. 14, the FOPI controller reduce the disturbance with a lower settling-time but with a higher overshoot than the classical PI controller.

The proposed approach is evaluated over a real system BoostXL-Buck converter daughter card for a C2000 Delfino Launchpad by Texas Instruments. The microcontroller and the Synchronous Buck converter are presented in Fig. 15. The measurements are performed by using a UNI-T Oscilloscope with two channels, 100MHz Bandwidth, and a 1 GS/s sampling frequency.

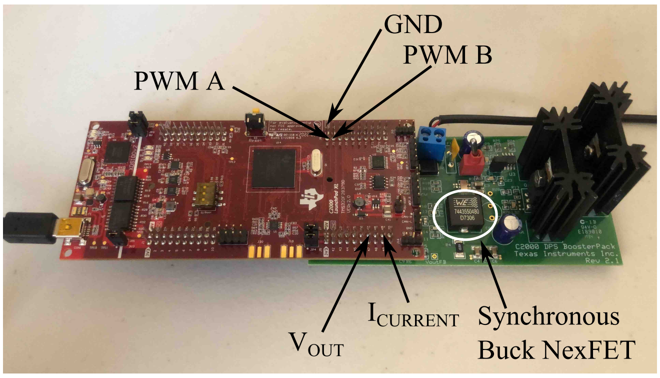

Fig. 15. Synchronous Buck converter and C2000 processor

The controller implementation is performed in Simulink-Matlab by using the C2000 embedded coder support package. An example of a classical PI controller for the Synchronous Buck converter of Fig. 15 is shown in Fig. 16.

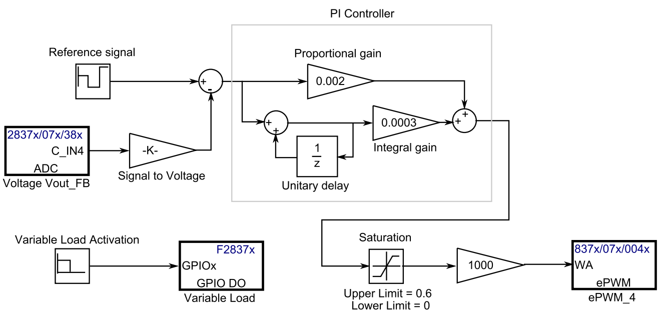

Fig. 16. Classical PI control diagram for Synchronous Buck converter and C2000 processor

An example of the Fractional Order PI controller for the Synchronous Buck converter is shown in Fig. 17.

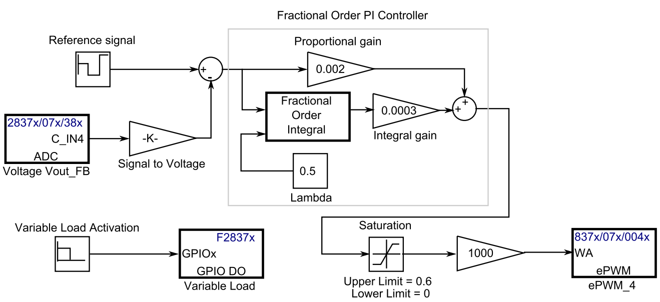

Fig. 17. Classical Fractional Order PI control diagram for Synchronous Buck converter and C2000 processor

The PWM Block can be configured for several PWM switching frequencies. A trial for a PWM switching frequency of 30kHz is shown in Fig. 18. The PWM A and PWM B are configured within the block, where the dead-zone for the PWM is also configured. In this case, a dead-zone of 20 clock cycles, being a clock cycle $1/200MHz$, is used.

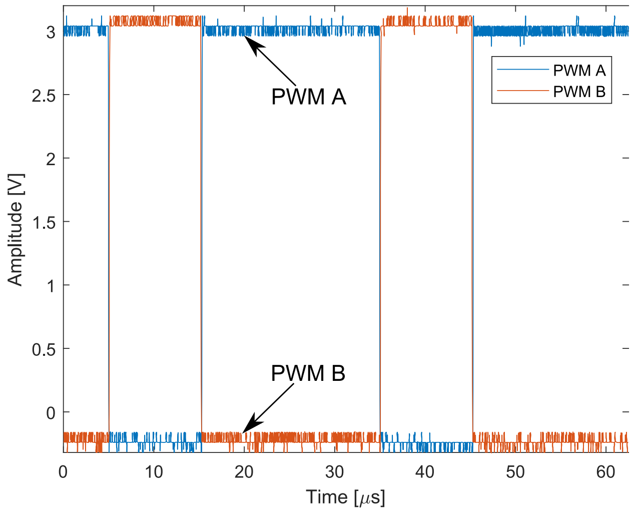

Fig. 18. PWM A and B for 30kHz switching frequency

The tracking performance for a classical PI Voltage variation with a PWM of 30kHz is shown in Fig. 19.

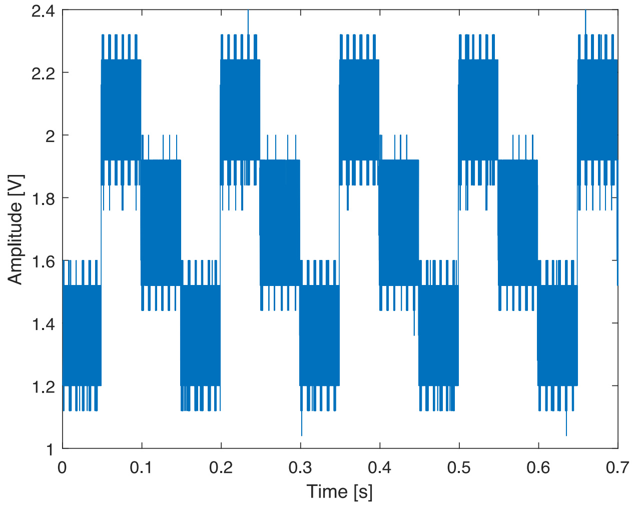

Fig. 19. Voltage reference tracking performance for a PWM of 30kHz and a classical PI controller

For a PWM switching frequency of 200kHz, the resulting PWM A and PWM B are presented in Fig. 20.

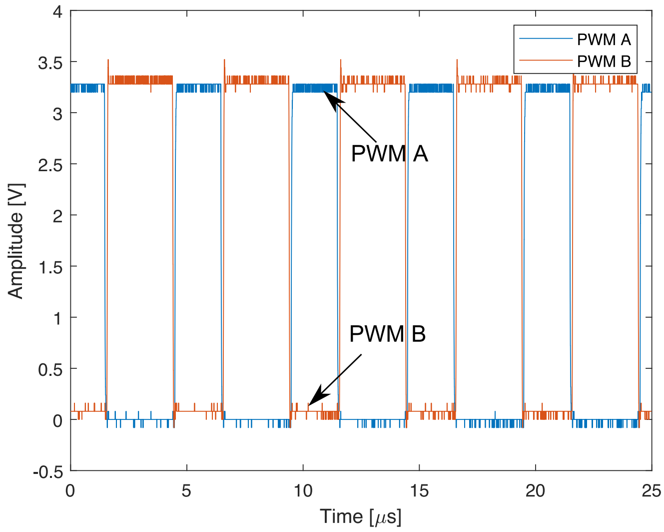

Fig. 20. PWM 200kHz

The reference tracking performance of the classical PI controller by using a 200kHz PWM is shown in Fig. 21.

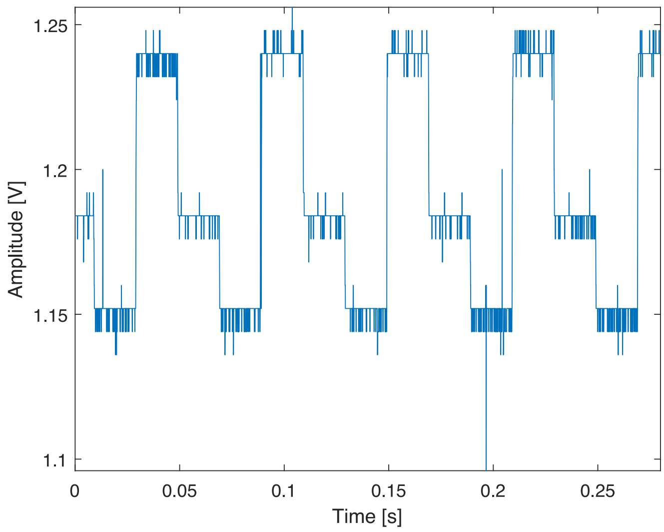

Fig. 21. Reference tracking for a voltage variation with a PWM 200kHz and a classical PI controller

It is worth mentioning that by comparing the Fig. 19 and Fig. 21, the 200kHz switching frequency reduces the voltage variation around the steady state output signal.

The reference tracking considering a voltage variation with a PWM 200kHz and a FOPI controller is shown in Fig. 22

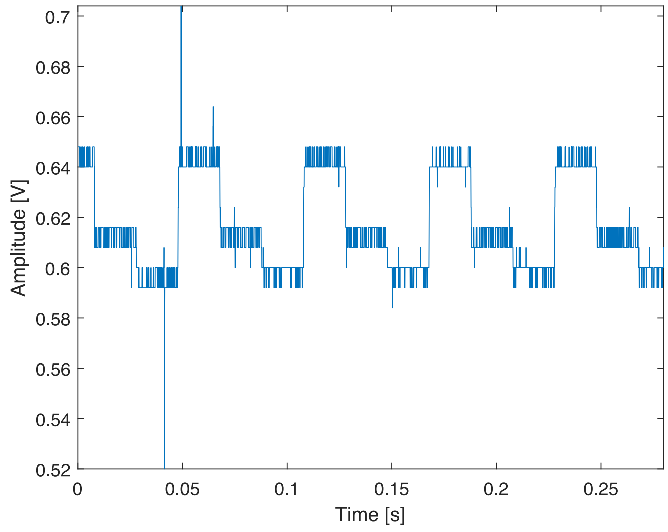

Fig. 22. Reference tracking for a voltage variation with a PWM 200kHz and a FOPI controller

In Fig. 23 is shown the oscilloscope capture for a reference tracking from 0V to 2.2V by using the FOPI controller, and by considering voltage and current measurements.

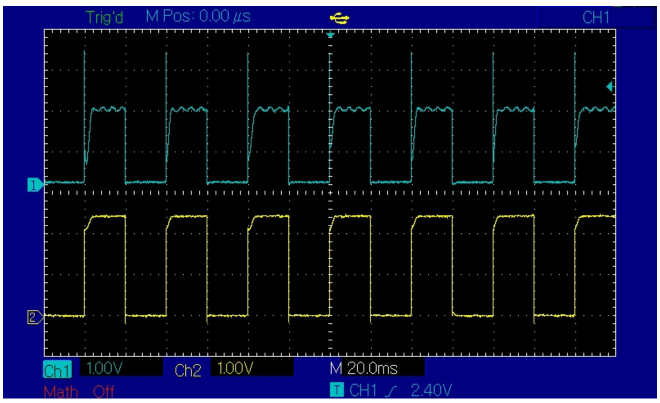

Fig. 23. Reference tracking for 0V to 2.2V variable reference signal for voltage output (yellow) and current (blue)

IV. Conclusions

In this work, an embedded Fractional Order Proportional-Integral is proposed, evaluated and validated in simulation and in real-time over a Synchronous Buck converter. A detailed comparison analysis is performed for two scenarios: reference tracking and variable load. The comparison is performed by using a classical PI approach which is the most used controller for this type of application. It can be seen that in both scenarios the FOPI outperformed the classical PI performance for reference tracking and disturbance rejection considering a variable load. In addition, an analysis of switching frequency in terms of harmonic distortion is performed, where the 200 kHz switching frequency is selected due to the quality of the output signal.

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